

Strangeness and meson-nucleon sigma terms

Harleen Dahiya and Neetika Sharma

*Department of Physics, Dr. B.R. Ambedkar National Institute of Technology, Jalandhar,
Punjab-144 011, India.*

Abstract.

The chiral constituent quark model (χ CQM) has been extended to calculate the flavor structure of the nucleon through the meson-nucleon sigma terms which have large contributions from the quark sea and are greatly affected by chiral symmetry breaking and SU(3) symmetry breaking. The hidden strangeness component in the nucleon has also been investigated and its significant contribution is found to be consistent with the recent available experimental observations.

Keywords: Strangeness in the nucleon, chiral symmetry breaking, chiral constituent quark model

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The knowledge on the internal structure of the nucleon has been rather limited because of confinement and it is still a big challenge to perform the calculations from the first principles of Quantum Chromodynamics (QCD). The measurements of polarized structure functions of proton in the deep inelastic scattering (DIS) experiments [1] provided the first evidence that the valence quarks of proton carry only a small fraction of its spin in contradiction with the predictions of the Naive Quark Model (NQM) [2].

Several interesting facts have also been revealed regarding the flavor distribution functions [3] indicating that the structure of the nucleon is not limited to u and d quarks only. Recently, there have been indications of non-zero strangeness content in the nucleon by the experiments measuring electromagnetic form factors [4] as well as in the context of low-energy experiments [5, 6].

The meson-nucleon sigma terms [6] are the fundamental parameters to test the chiral symmetry breaking effects and thereby determine the scalar quark content of the baryons. They are theoretically interesting because they are known to have intimate connection with the dynamics of the non-valence quarks at low-energy [7, 8, 9].

We plan to understand the implications of chiral symmetry breaking for the scalar matrix elements of the nucleon within the chiral constituent quark model (χ CQM) [10, 11, 12, 13]. In particular, we would like to phenomenologically estimate the quantities affected by the hidden strangeness component in the nucleon as well as to study the meson-nucleon sigma terms and the meson-baryon sigma terms for Σ and Ξ baryons which are expected to have large contributions from the quark sea.

The key to understand the χ CQM formalism [14], is the fluctuation process $q^\pm \rightarrow \text{GB} + q'^\mp \rightarrow (q\bar{q}') + q'^\mp$, where $q\bar{q}' + q'$ constitute the “quark sea” [11, 14, 15]. The effective Lagrangian describing the interaction between quarks and a nonet of GBs can be expressed as $\mathcal{L} = g_8 \bar{\mathbf{q}} \left(\Phi + \zeta \frac{\eta'}{\sqrt{3}} I \right) \mathbf{q} = g_8 \bar{\mathbf{q}} (\Phi') \mathbf{q}$.

The flavor structure of the nucleon is defined as [14] $\hat{N} \equiv \langle N | q\bar{q} | N \rangle$ where $|N\rangle$ is the nucleon wavefunction and $q\bar{q}$ is the number operator for the scalar quark content

measuring the sum of the quark and antiquark numbers. The pion-nucleon sigma term ($\sigma_{\pi N}$) affected by the contributions of the quark sea is expressed as

$$\sigma_{\pi N} = \hat{m} \frac{\langle N | \bar{u}u + \bar{d}d - 2\bar{s}s | N \rangle}{1 - 2y_N} = \frac{\hat{\sigma}}{1 - 2y_N}, \quad (1)$$

where we have defined

$$\hat{\sigma} = \hat{m} \langle N | \bar{u}u + \bar{d}d - 2\bar{s}s | N \rangle \quad \text{and} \quad y_N = \frac{\langle N | \bar{s}s | N \rangle}{\langle N | \bar{u}u + \bar{d}d | N \rangle}. \quad (2)$$

The strangeness fraction of the nucleon and strangeness sigma term are respectively defined as

$$f_s = \frac{\langle N | \bar{s}s | N \rangle}{\langle N | \bar{u}u + \bar{d}d + \bar{s}s | N \rangle} = \frac{\sigma_{\pi N} - \hat{\sigma}}{3\sigma_{\pi N} - \hat{\sigma}} \quad \text{and} \quad \sigma_s = m_s \langle N | \bar{s}s | N \rangle = \frac{1}{2} y_N \frac{m_s}{\hat{m}} \sigma_{\pi N}. \quad (3)$$

Further, the sigma terms corresponding to the strange mesons can be expressed as

$$\sigma_{KN} = \frac{\sigma_{KN}^u + \sigma_{KN}^d}{2} = \frac{\hat{m} + m_s}{2} \langle N | \bar{u}u + \bar{d}d + 2\bar{s}s | N \rangle = \frac{\hat{m} + m_s}{4\hat{m}} (2\sigma_{\pi N} - \hat{\sigma}), \quad (4)$$

$$\sigma_{\eta N} = \frac{1}{3} \langle N | \hat{m}(\bar{u}u + \bar{d}d) + 2m_s\bar{s}s | N \rangle = \frac{1}{3} \hat{\sigma} + \frac{2(m_s + \hat{m})}{3\hat{m}} y_N \sigma_{\pi N}. \quad (5)$$

The SU(3) symmetric and antisymmetric scalar matrix elements characterizing the weak matrix elements for the flavor structure are expressed as

$$F_S = \frac{1}{2} \langle N | \bar{u}u - \bar{s}s | N \rangle, \quad D_S = \frac{1}{2} \langle N | \bar{u}u - 2\bar{d}d + \bar{s}s | N \rangle. \quad (6)$$

Similarly, the singlet and non-singlet combinations of the flavor structure can be related to the weak couplings and are expressed as

$$g_A^0 = \langle N | \bar{u}u + \bar{d}d + \bar{s}s | N \rangle, \quad g_A^3 = \langle N | \bar{u}u - \bar{d}d | N \rangle, \quad g_A^8 = \langle N | \bar{u}u + \bar{d}d - 2\bar{s}s | N \rangle. \quad (7)$$

In Table 1, we have presented the results of our calculations pertaining to the scalar matrix elements affected by the strangeness content of the nucleon. To understand the implications of the strange quark mass and SU(3) symmetry breaking, we have presented the results with and without SU(3) symmetry breaking. From the Table one finds that the present result for the strangeness content in the nucleon y_N and strangeness fraction of the nucleon f_s looks to be in agreement with the most recent experimental and phenomenological results available. The non-zero values for y_N and f_s in the present case indicate that the chiral symmetry breaking is essential to understand the significant role played by the quark sea. It is also clear from the table that, in general, the quantities involving the strange quark content are very sensitive to SU(3) symmetry breaking. For example, the values of the strangeness dependent quantities y_N , f_s , F_S , D_S , G_s^0 , G_s^8 , $\hat{\sigma}$, σ_s , $\sigma_{\pi N}$, σ_{KN} , and $\sigma_{\eta N}$ change to a large extent when compared for the SU(3) symmetric

TABLE 1. The χ CQM results for the scalar matrix elements of the nucleon.

Quantity	Phenomenology	NQM [2]	χ CQM	
			with SU(3) symmetry	with SU(3) symmetry breaking
$\langle N|\bar{u}u|N\rangle$...	≤ 2	2.41	2.44
$\langle N|\bar{d}d|N\rangle$...	≤ 1	1.75	1.68
$\langle N|\bar{s}s|N\rangle$	...	0.0	1.08	0.18
y_N	0.11 ± 0.07 [7]	0.0	0.26	0.044
f_s	0.10 ± 0.06 [5]	0.0	0.21	0.042
F_s	1.52 [17], 1.81 [7]	≤ 1	0.67	1.13
D_s	-0.52 [17], -0.57 [7]	0.0	0.0	-0.37
R_s	...	≤ 3	6.22	5.39
G_S^0	...	≤ 3	5.24	4.30
G_S^{00}	...	≤ 1	0.67	0.76
G_S^{000}	...	≤ 3	2.01	3.76
$\hat{\sigma}$	...	28.57	28.57	28.57
σ_s	...	0	168.71	15.12
$\sigma_{\pi N}$	...	28.57	59.25	31.32
σ_{KN}	...	164.29	517.04	195.90
$\sigma_{\eta N}$	...	9.52	244.70	30.60

and SU(3) symmetry breaking case. The results for other quantities which do not have strangeness contribution are not much different for both the cases.

For $\sigma_{\pi N}$, the value of χ CQM with SU(3) symmetry can give a value in the higher range by adopting a larger value of $\hat{\sigma}$ however, as has been shown in our earlier work [11], SU(3) symmetry does not give a satisfactory description of quark sea asymmetry and spin related quantities. A refinement in the analysis of $\pi - N$ scattering giving higher values of $\sigma_{\pi N}$ would not only strengthen the mechanism of chiral symmetry breaking generating the appropriate amount of strangeness in the nucleon but would also justify the consequences of SU(3) symmetry breaking mechanism.

The calculations can be extended to predict the meson-nucleon sigma terms (σ_{KN} and $\sigma_{\eta N}$) as well as the meson-baryon sigma terms for Σ and Ξ baryons (Table 2). The σ_{KN} and $\sigma_{\eta N}$ terms are found to be quite sensitive to y_N and also become strangely large for the SU(3) symmetric case. The future DAΦNE experiments [16] to determine KN sigma terms could restrict the model parameters and provide better knowledge of strangeness content of the nucleon which would also have important implications for the hyperon-antihyperon production in the heavy ion collisions.

In conclusion, we would like to state that chiral symmetry breaking is the key to understand the hidden strangeness content of the nucleon. In the nonperturbative regime of QCD, constituent quarks and the weakly interacting Goldstone bosons constitute the appropriate degrees of freedom at the leading order.

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TABLE 2. The χ CQM results for the meson-baryon sigma terms.

Baryon (B)	$\sigma_{\pi B}$	σ_{KB}	$\sigma_{\eta B}$
N	31.32	195.90	30.60
Σ	137.76	1419.97	846.65
Ξ	-17.96	-370.76	-347.17

REFERENCES

1. J. Ashman *et al.* (EMC Collaboration), Phys. Lett. B **206**, 364 (1988); Nucl. Phys. B **328**, 1 (1989); P.L. Anthony *et al.* (E142 Collaboration), Phys. Rev. Lett. **71**, 959 (1993); K. Abe *et al.* (E143 Collaboration), Phys. Rev. Lett. **76**, 587 (1996); P. Adams *et al.*, Phys. Rev. D **56**, 5330 (1997); K. Abe *et al.* (E154 Collaboration), Phys. Rev. Lett. **79**, 26 (1997); B. Adeva *et al.* (SMC Collaboration), Phys. Rev. D **58**, 112001 (1998); A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. D **71**, 012003 (2005).
2. A. De Rujula, H. Georgi, and S.L. Glashow, Phys. Rev. D **12**, 147 (1975); A. Le Yaouanc, L. Oliver, O. Pene, and J.C. Raynal, Phys. Rev. D **15**, 844 (1977); M. Gupta and A.N. Mitra, Phys. Rev. D **18**, 1585 (1978); N. Isgur and G. Karl, Phys. Rev. D **21**, 3175 (1980); P. Geiger and N. Isgur, Phys. Rev. D **55**, 299 (1997).
3. P. Amaudruz *et al.* (New Muon Collaboration), Phys. Rev. Lett. **66**, 2712 (1991); M. Arneodo *et al.*, Phys. Rev. D **50**, R1 (1994); E.A. Hawker *et al.* (E866/NuSea Collaboration), Phys. Rev. Lett. **80**, 3715 (1998); J.C. Peng *et al.*, Phys. Rev. D **58**, 092004 (1998); R.S. Towell *et al.*, Phys. Rev. D **64**, 052002 (2001).
4. D.T. Spayde *et al.* (SAMPLE Collaboration), Phys. Lett. B **583**, 79 (2004); D. Armstrong *et al.* (G0 Collaboration), Phys. Rev. Lett. **95**, 092001 (2005); F.E. Maas *et al.* (A4 Collaboration), Phys. Rev. Lett. **94**, 152001 (2005); K.A. Aniol *et al.* (HAPPEX Collaboration), Phys. Rev. Lett. **98**, 032301 (2007); Eur. Phys. J. A **31**, 597 (2007).
5. A.O. Bazarko *et al.* (CCFR Collaboration and NuTeV Collaboration), Z. Phys C **65**, 189 (1995).
6. E. Reya, Rev. Mod. Phys. **46**, 545 (1974); R. L. Jaffe, Phys. Rev. D **21**, 3215 (1980); J. Gasser and M.E. Sainio, in Physics and Detectors for DAΦNE, edited by S. Bianco *et al.* (Frascati, 1999); M.E. Sainio, PiN Newslett. **16**, 138 (2002).
7. J. Gasser and H. Leutwyler, Phys. Rep. **87**, 77 (1982); J. Gasser, Ann. Phys. (NY) **136**, 62 (1982); M. Nagy and M.D. Scadron, Acta. Phys. Slov. **54**, 427 (2003).
8. Riazuddin and Fayyazuddin, Phys. Rev. D **38**, 944 (1988).
9. Steven D. Bass, Phys. Lett. B **463**, 286 (1999); Czech. J. Phys. **50**, 109 (2000); Nucl. Phys. Proc. Suppl. **105**, 56 (2002); J. Ellis, Eur. Phys. J. A **24** S2, 3 (2005); M.D. Scadron, F. Kleefeld, and G. Rupp, hep-ph/0609024; G. Dillon and G. Morpurgo, Phys. Rev. D **75**, 073007 (2007).
10. S. Weinberg, Physica A **96**, 327 (1979); A. Manohar and H. Georgi, Nucl. Phys. B **234**, 189 (1984); E.J. Eichten, I. Hinchliffe, and C. Quigg, Phys. Rev. D **45**, 2269 (1992).
11. H. Dahiya and M. Gupta, Phys. Rev. D **64**, 014013 (2001); **67**, 074001 (2003); H. Dahiya and M. Gupta, Int. Jol. of Mod. Phys. A, Vol. 19, No. 29, 5027 (2004); H. Dahiya, M. Gupta and J.M.S. Rana, Int. Jol. of Mod. Phys. A, Vol. 21, No. 21, 4255 (2006); H. Dahiya and M. Gupta, Phys. Rev. D **78**, 014001 (2008).
12. H. Dahiya and M. Gupta, Phys. Rev. D **66**, 051501 (R) (2002); **67**, 114015 (2003); N. Sharma, H. Dahiya, P.K. Chatley, and M. Gupta, Phys. Rev. D **79**, 077503 (2009); N. Sharma, H. Dahiya, and P.K. Chatley, Eur. Phys. J. A **44**, 125 (2010).
13. H. Dahiya and M. Gupta, Eur. Phys. J. C **52**, 571 (2007); N. Sharma and H. Dahiya, Phys. Rev. D **81**, 114003 (2010).
14. T.P. Cheng and L.F. Li, Phys. Rev. Lett. **74**, 2872 (1995); Phys. Rev. D **57**, 344 (1998); Phys. Rev. Lett. **80**, 2789 (1998); X. Song, Phys. Rev. D **57**, 4114 (1998).
15. J. Linde, T. Ohlsson, and H. Snellman, Phys. Rev. D **57**, 452 (1998); **57**, 5916 (1998).
16. P.M. Gensini, R. Hurtado, and G. Violini, arXiv:hep-ph/9804344.
17. L. Maiani *et al.*, Nucl. Phys. **293**, 420 (1987); M. Osaka, Nucl. Phys. B (Proc Suppl.) **47**, 160 (1996).